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A SEMI-CLASSICAL DESCRIPTION OF GIANT RESONANCES AT FINITE TEMPERATURE [1]

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RESUME

Nous présentons une étude de la dépendance en température de l'énergie des résonances géantes isoscalaires, a l'aide d'un modèle semi-classique, et dans le cadre de la procédure de soustraction de Bonche, Levit et Vautherin. Cette prescription permet un traitement cohérent des effets du continu, qui, comme nous le montrons de facon détaillée, jouent un role crucial dans la description des états collectifs excités. Une attention toute particulière est portée a la résonance monopolaire pour laquelle nous avons calculé 3 moments de la fonction de strength. Nous trouvons une faible dépendance en température de l'énergie des résonances étudiées (l=0,2,3,4).

ABSTRACT

We present a study of the temperature dependance of the energies of isoscalar giant resonances within a semi-classical model, in the framework of the subtraction procedure of Bonche, Levit and Vautherin. This prescription allows a consistent treatment of continuum effects, which play, as we show in detail, a crucial role in the description of excited collective motions. Special attention is paid to the monopole resonance for which 3 moments of the strength function have been calculated. We find a weak temperature dependance of the studied resonance energies (l=0,2,3,4).

INTRODUCTION

The study of excited collective nuclear motion is presentlu of challenging interest, both theoretically and experimentally, after the recent observation of these phenomena [1]. The description of such states is delicate, due to the metastability, with respect to particle emission, of excited nuclei. Dynamical calculations have been undertaken and have shown

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that, at not too high temperatures ($T \lesssim 5$-6MeV), the evaporation does not drastically affect the system, so that it is reasonable to picture a hot nucleus embedded in an external gas generated during the vibration [2]. Such a situation justifies the use of finite temperature RPA approaches, provided the system is artificially stabilized, using some physically sounded prescription. Non self-consistent treatments of the continuum, either in Hartree-Fock (HF) [3] or Thomas-Fermi (TF) [4] formalisms unfortunately restrict the validity of the calculations to low temperatures ($T \lesssim 2$-3MeV). Recently Bonche, Levit and Vautherin (BLV) have proposed a " subtraction procedure " which allows to deal with a well defined physical situation, at any temperature, and with a definite way of distinguishing between the nucleus and the evaporated nucleons [5]. The purpose of this note is to present a semi-classical description of Giant Resonances in the BLV formalism after having showed the crucial importance of continuum effects in this context.

THE MODEL

A rough picture of the BLV method is of equilibrating the hot nucleus by an external gas such that the flow of nucleons leaving the nucleus is exactly compensated by a flow of entering nucleons. More precisely, mean-field equations have, at given temperature and chemical potential, 2 distinct solutions, respectively associated to a nucleus in equilibrium with its evaporated nucleons (NG) and to a gas-like phase of nearly free nucleons (G) [6]. It is hence possible to define a " subtracted " thermodynamical potential $\underline{\Omega}$ whose coupled HF solutions $(\Phi_i, n_i)^{NG,G}$ will define the isolated hot nucleus [5].

In the framework of our semi-classical calculations the hot nucleus is simply described by 2 density profiles $\rho^{NG}(r)$ and $\rho^{G}(r)$ (within omitting isospin indexes), respectively representing the nucleus+gas and the gas phases in equilibrium [7]. The subtracted thermodynamical potential $\underline{\Omega}[\rho^{NG}, \rho^{G}]=\Omega[\rho^{NG}]-\Omega[\rho^{G}]+E_c(\rho^{NG}, \rho^{G})$ can be obtained from the grand potentials Ω of each phase and the Coulomb energy E_c. The Coulomb term is calculated for the density $\rho^{NG} - \rho^{G}$ of the isolated nucleus, which eliminates spurious polarization effects of the vapor phase by the Coulomb field of the nucleus [5]. The equilibrium state of the system is then simply obtained as a saddle point of $\underline{\Omega}$ with respect to the variations of both $\rho^{NG}(r)$ and $\rho^{G}(r)$. Once the equilibrium is obtained, any average thermodynamical quantity can be estimated from ρ^{NG}, ρ^{G}

Working in a static semi-classical approach we are left with describing the Giant Resonances through the moments m_k of the strength function S(E). Except for the inverse energy weigthed sum rule $m_{-1}(l=0)$, which is obtained from a constrained calculation, the moments $m_{1,3}(l=0,2,3,4)$ are simply given, at zero [8] and finite [9] temperature, by integrals involving the nuclear density. Note that, as the moments are extensive quantities, they are to be understood, in the BLV formalism, as the difference between their values respectively calculated for the NG and G-like phases. Notice also that the expressions we use for $m_{1,3}(l=0,2,3,4)$ are exact within the RPA, the semi-classical approximation being introduced only in the last step, to evaluate the moments numerically.

For calculating $m_{-1}(l=0)$ we perform a constrained calculation in which the collective operator $Q = \lambda \langle r^2 \rangle$ acts on the nucleus itself i.e. on the $\rho^{NG} - \rho^{G}$ density only. The polarizability of the system is then simply given by

$$m_{-1} = -\frac{1}{2} A \frac{d \langle r^2(\lambda) \rangle}{d\lambda}\Big|_{\lambda=0}$$

with

$$\langle r^2 \rangle = \int_0^\infty (\rho^{NG} - \rho^{G})(r)\, d^3r$$

In the following we shall discuss results obtained for the 2 standart estimates E_1 and E_3 of the resonance energies

$$E_1 = \sqrt{\frac{m_1}{m_{-1}}} \quad , \quad E_3 = \sqrt{\frac{m_3}{m_1}}$$

At zero temperature E_1 and E_3 also provide an upper bound for the width Γ of the resonance ($\Gamma^2 \propto (E_3^2 - E_1^2)$). At finite temperature, with the opening of new transitions at very low energy, this definition of Γ does not hold anymore, or at least does not describe the resonance itself.

All our calculations have been performed with the Skyrme SKM* interaction, together with a phenomenological Extended Thomas Fermi approximation for the kinetic energy density. We have checked that this functional gives results in good agreement with zero temperature HF calculations of RPA sum rules [9] and with the original BLV finite temperature HF results [5].

SUBTRACTED VERSUS NON SUBTRACTED CALCULATIONS

In order to evaluate quantitatively the importance of spurious continuum effects, which have recently been observed in dynamical approaches [10], we have performed "non subtracted" (NS) calculations. In this case the nucleus is described by a single density profile ρ (r) whose equilibrium shape is obtained by minimizing the free energy.

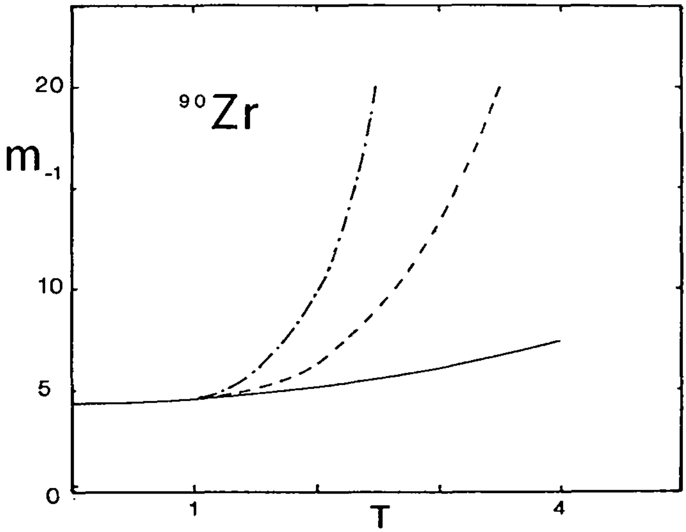

Figure 1

Values of non subtracted (dashed line for box size R=12fm, and dashed-dotted line for R=14fm) and subtracted (full line) inverse energy weigthed sum rule m_{-1} (in 10^2 MeV $^{-1}$ fm ^{4}) as a function of the temperature **T** (in MeV) in the case of ^{90}Zr. Note the rapid (spurious) increase of m_{-1} for non subtracted calculations at very low temperatures (T>1MeV). This increase of m_{-1} explains the collapse of the E_1 energy as showed in Figure 2.

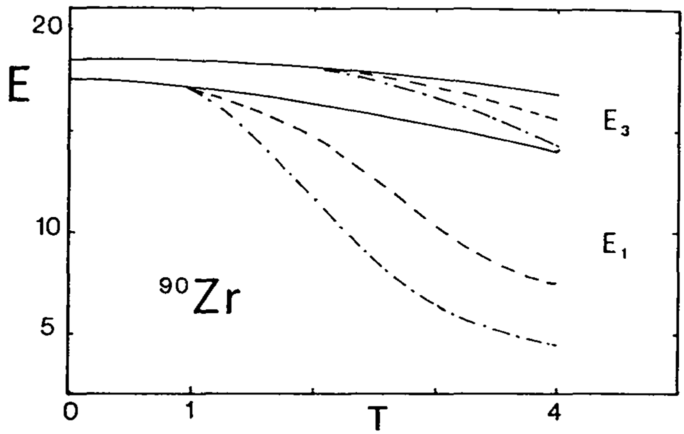

Figure 2

Values of non subtracted (dashed line for box size R=14fm, and dashed-dotted line for R=12fm) and subtracted (full line) E_1 and E_3 energies (in MeV) as a function of the temperature **T** (in MeV) in the case of ^{90}Zr. Note the large spurious continuum effects (see text) for the non subtracted values of E_1 as soon as the temperature is greater than 1 MeV.

In Figure 1 are plotted the values of $m_{-1}(T)$ obtained from 2 NS calculations (box radii R=12fm and R=14fm) and a subtracted one, for ^{90}Zr . From this figure one can see that m_{-1} strongly depends on R and T in the NS case, while the temperature dependance is very weak in the subtracted case. The NS $m_{1,3}(l=0)$ values are much closer to the subtracted results, which indicates that continuum effects mainly concern the low energy part of the strength function. As a consequence the NS value of the $E_1(l=0)$ energy collapses with increasing temperature as is presented in Figure 2. This over-increase of m_{-1} reflects the populating, at finite temperature, of low-lying states, to which m_{-1} is particularly sensitive, and whose energies can be identified with eigenmode frequencies of the box [10]. In our semi-classical approach this spurious effect reflects the response of the non-vanishing gas part of the density profile $\rho(r)$ to the r^2 collective operator, an effect which naturally disappear in subtracted calculations. The same spurious behaviour appears for higher multipolarities, for which even the E_3 values are affected as can clearly be seen from Figure 3.

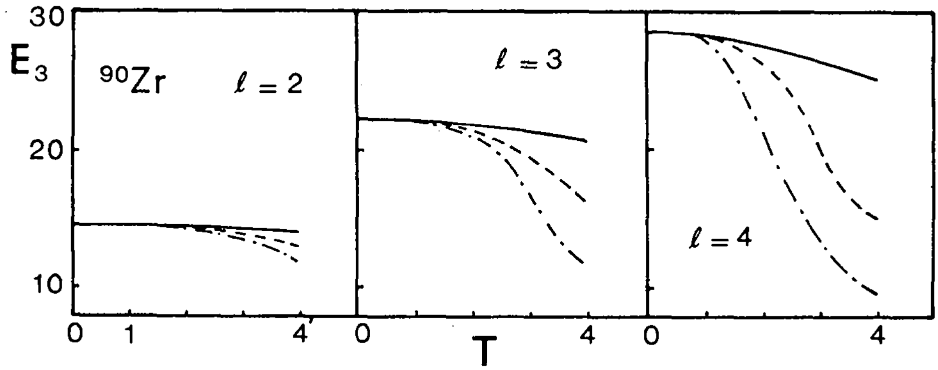

Figure 3

Same as Figure 2 for the E_3 energy of the l=2,3,4 giant resonances in ^{90}Zr (same units and notations).

RESULTS

Spurious box effects being eliminated in our subtracted framework, we have studied the resonance energies of various nuclei. Some characteristic examples (^{90}Zr, ^{120}Sn and ^{208}Pb) are showed in Figure 4, for the monopole case, and in Figure 5 for l=2,3,4.

The first conclusion arising from the study of Figure 4 is that the monopole energy very weakly decreases with increasing temperature, which reflects a smooth softening of nuclear matter. In addition, although the width of the resonance cannot be directly evaluated from E_1 and E_3 because of the possible occupation of low-lying non-collective states, one can estimate that the spreading of the monopole resonance is very small, as E_1 and E_3 stay very close together for any temperature.

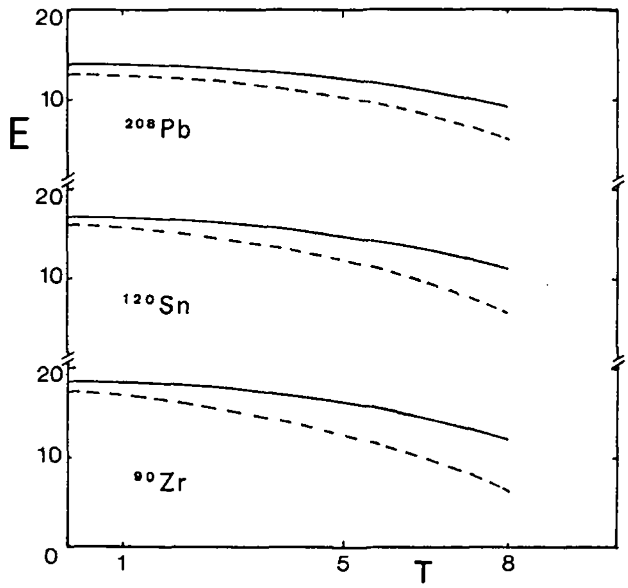

Figure 4

Variations of the E_1 **(dashed line)** and E_3 **(full line)** energies (in MeV) of the giant monopole resonance as a function of the temperature **T** (in MeV) for the 3 nuclei **^{90}Zr, ^{120}Sn** and **^{208}Pb**. Note the very weak decrease of the resonance energy (which lies between E_1 and E_3) with increasing temperature, and, as E_1 and E_3 stay very close together, the presumably small spreading of the collective mode.

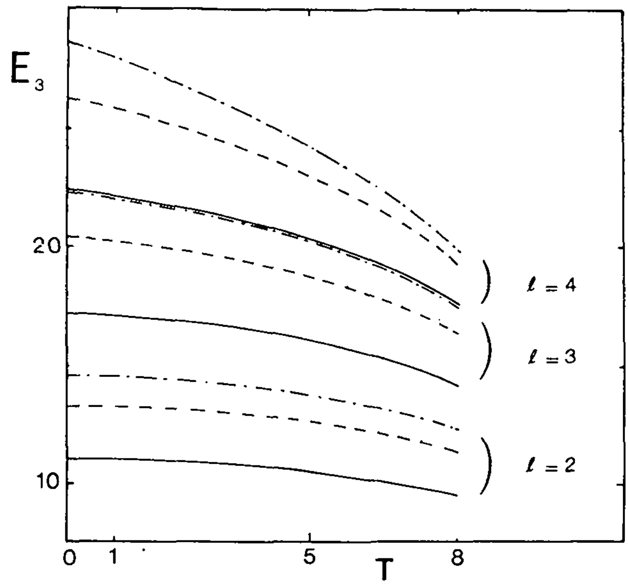

Figure 5

Variations of the E_3 energies (in MeV) of the **l=2,3,4** giant resonances in **^{90}Zr** (dashed-dotted line), **^{120}Sn** (dashed line) and **^{208}Pb** (full line), as a function of the temperature **T** (in MeV). Note the remarkable stability of the quadrupole energy.

Concerning higher multipolarities one can note that the E_3 energies also little depend on the temperature, all the less for low multipolarities and big nuclei. The first trend reflects the facility in smoothing, by temperature effects, the numerous wiggles present in large-l deformed Fermi spheres. The second one is related to the fact that the surface, which crucially depends on the temperature, is more important in small than in big nuclei, so that the giant modes under consideration, which are essentially volume corrected by surface effects, are more sensitive to the temperature in small nuclei.

CONCLUSION

In this work we have applied a semi-classical subtracted formalism for estimating the temperature dependance of isoscalar giant resonances. We have showed the crucial importance of taking consistently into account continuum effects. We have found a weak temperature dependance of the resonance energies and estimated that the width of the giant monopole presumably also little depends on the temperature. Our results can unfortunately not be compared, for the moment, to the experimental data, which mainly concern the dipole resonance [1]. The spurious continuum effects pointed out in this note are anyhow essential for future works in this field. In particular we are presently trying to apply our subtracted formalism to the relevant case of the dipole resonance. As a final remark let us however note that excited monopole modes have recently been found in Landau-Vlasov simulations of fusion-like heavy-ion collisons, as is presented in the contribution of M.pi et al in this volume.

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